METEOROLOGICAL CONDITIONS AND TRANSPORT PATHWAYS DURING THE TRANSPORT AND CHEMICAL EVOLUTION OVER THE PACIFIC (TRACE-P) EXPERIMENT

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Submitted to

Journal of Geophysical Research
TRACE-P Special Section

October 2002
Revised January 2003

Abstract

The TRAnsport and Chemical Evolution over the Pacific (TRACE-P) Experiment was conducted between February and April 2001. It included extensive chemical sampling by two aircraft based primarily in Hong Kong and Yokota Air Base, Japan. TRACE-P examined pathways for the outflow of chemically and radiatively important gases and aerosols and their precursors from eastern Asia to the western Pacific, and explored the chemical evolution of Asian outflow. This paper describes meteorological conditions and transport pathways over the Pacific Basin during TRACE-P. Meteorological conditions changed rapidly during the period due to the seasonal winter to spring transition and the decay of prolonged ENSO cold phase (La Nina) conditions. To document these changes, TRACE-P was divided into two halves, and mean flow patterns during each half are presented and discussed. Important circulation features are the semi-permanent Siberian anticyclone and transient middle latitude cyclones that form near eastern Asia and then move eastward over the northern Pacific. Five-day backward trajectories from the various flight tracks show that air sampled by the aircraft had been transported from a variety of locations. Some parcels remained over the tropical western North Pacific during the entire period, while other important origins were Southeast Asia, Africa, and central Asia. Specifically, lower tropospheric flight segments out of Hong Kong sampled both pre-frontal maritime air as well as post-frontal air from the Asian continent. Conversely, low-level flight segments out of Yokota, Japan mostly sampled post-frontal Asian air. Southern portions of middle and upper tropospheric flight segments from Hong Kong sampled air previously in the deep tropics, while the more northerly flight segments sampled air that originated from the west (e.g., passing over central Africa and India). Most upper level flight segments from Yokota sampled air arriving from the west. Patterns of satellite-derived precipitation and lightning are described. TRACE-P occurs during a neutral to weak La Nina period of relatively cold sea surface temperatures in the tropical Pacific. Compared to climatology, the TRACE-P period exhibits deep convection located west of its typical position; however, tropospheric flow patterns do not exhibit a strong La Nina signal. Circulation patterns during TRACE-P are found to be generally similar to those during NASA's PEM WEST-B mission that occurred in the same region during February – March 1994.

1. Introduction

The TRAnsport and Chemical Evolution over the Pacific (TRACE-P) Experiment was conducted over the northwestern Pacific Basin between February and April 2001 as part of NASA's Global Tropospheric Experiment (GTE) [*McNeal et al.,* 1984]. Previous GTE missions over the northwestern Pacific were the Pacific Exploratory Missions (PEM)—West, Parts A and B [*Hoell et al.,* 1996, 1997]. In addition, the PEM-Tropics A and B missions were conducted over the tropical and South Pacific [*Hoell et al*., 1999; *Raper et al*., 2001]. The goals of TRACE-P were 1) to determine pathways for the outflow of chemically and radiatively important gases and aerosols and their precursors from eastern Asia to the western Pacific, and 2) to determine the chemical evolution of Asian outflow over the western Pacific and understand the ensemble of processes that control this evolution [*Jacob et al*., this issue].

Meteorological conditions play a vital role in determining the transport and distribution of many chemical species [e.g., *Merrill et al*., 1997]. For example, atmospheric temperature and humidity affect chemical reaction rates and thereby influence the lifetimes of many species [e.g., *Mauzerall et al*., 1998; *Blake et al*., 2001; *Martin et al.*, 2002]. Precipitation can scavenge some species (e.g., *Cohan et al*. [1999], *O'Sullivan et al.* [1999]), while lightning can create species such as nitrogen oxides [e.g., *Lawrence et al*., 1994]. Deep convection and smaller scale turbulent mixing transport surface-based species into the free troposphere where they can be carried vast distances by strong upper-level winds [e.g., *Maloney et al.,* 2001]. In addition, phases in the El Nino-Southern Oscillation (ENSO) can alter large scale transport patterns [e.g., *Trenberth et al*., 1997].

TRACE-P occurred during the transition from winter to spring conditions, and during a period when the phase of ENSO was changing rapidly. The current paper details the atmospheric changes that were observed during the TRACE-P period (February 23 – April 9, 2001), describing the large scale, persistent flow patterns, the resulting transport pathways over the Pacific Basin, and their changes during the seven week TRACE-P mission. Distributions of precipitation and lightning also are described. Finally, we examine departures of the TRACE-P period from climatology, assess the role of the ENSO, and compare conditions during TRACE-P with those of a previous GTE mission in the same area (PEM West-B).

2. Data and Methodologies

TRACE-P employed two NASA aircraft to collect extensive in situ chemical and meteorological data. The DC-8 conducted 17 science flights, while the P-3B conducted 18 flights. These flights stretched from California to the coast of central Asia and from northern Japan to near Southeast Asia (Figure 3 in *Jacob et al.* [this issue]). Although the area of these flights is the major focus of this paper, we also consider various upwind regions whose meteorology affects the TRACE-P domain.

Our streamline analyses and cross sections were derived from reanalysis data prepared by the National Centers for Environmental Prediction (NCEP) [*Kalnay et al.,* 1996; *Kistler et al*., 2001] and available on the web site of the NOAA-CIRES Climate Diagnostics Center (CDC) at URL http://www.cdc.noaa.gov. Outgoing long-wave radiation data obtained from the CDC web site were computed using the procedure of *Liebmann et al*. [1996].

Our trajectories utilized global gridded meteorological analyses prepared by the European Centre for Medium-Range Weather Forecasts (ECMWF) [*Bengtsson*, 1985; *Hollingsworth et al*., 1986, *ECMWF*, 1995]. We compared the ECMWF and NCEP data sets during TRACE-P and found very close agreements, similar to the conclusion of *Merrill et al.* [1997] during PEM-West B, thereby permitting both data sources to be used in the current study. The ECMWF data were available four times daily (0000, 0600, 1200, and 1800 UTC) at 60 vertical levels with a T319 spherical harmonic triangular truncation, interpolated to a 1^{o} x 1^{o} latitude-longitude horizontal grid.

Five-day backward trajectories were calculated using a kinematic model, i.e., employing u, v, and w wind components from the ECMWF analyses. Due to the strong winds occurring over middle latitude portions of the TRACE-P area, this five–day period generally provided sufficient information about long-range transport without resorting to an even longer period whose results would be subject to greater uncertainty. Additional details about the trajectory model are given in *Fuelberg et al.* [1996, 1999, 2000]. Limitations of trajectories are described by *Fuelberg et al*. [2000], *Maloney et al*. [2001], *Stohl* [1998], and *Stohl et al*. [1995].

Lightning data are from the Lightning Imaging Sensor (LIS) that is onboard the Tropical Rainfall Measuring Mission (TRMM) satellite. The LIS detects total lightning (i.e., cloud-to-ground, intracloud, and cloud-to-cloud flashes) during both day and night [*Christian et al.,* 1999; *Christian*, 1999; NASA LIS Web site http://thunder.msfc.nasa.gov/lis.html]. Since the polar orbit of the TRMM satellite is inclined at 35^o, LIS only observes lightning between 35^{o}N – 35^{o}S, i.e., in the topics and subtropics where it is most common. Although LIS achieves an ~90% detection efficiency, its orbit does not provide continuous coverage. As a result, many flashes are not recorded. Nonetheless, the data are useful for studying global patterns qualitatively.

Satellite-derived rainfall estimates are from the SSM/I passive microwave sensor that is onboard the Defense Meteorological Satellite Program (DMSP) series of satellites [DMSP web site at http://www.ngdc.noaa.gov/dmsp/]. Rainfall currently is computed daily over the region 60^{o}S to 60^{o}N at a spatial resolution of 0.25^o x 0.25^o latitude/ longitude. The Ferriday rainfall algorithm that is used employs all four SSM/I frequencies as well as dual polarization information, with different algorithms used over land and ocean [*Ferriday and Avery*, 1994; NOAA web site http://www.etl.noaa.gov/climsat/].

3. Large-Scale Conditions

TRACE-P bridged the transition between winter and spring when meteorological conditions were undergoing major changes. In addition, since La Nina (cold phase ENSO) conditions were decaying rapidly, that decay also produced changes in large scale circulation patterns. Therefore, it is appropriate to divide the experiment period into halves, examining the flow patterns separately during each portion. The period February

23 through March 17, 2001 includes the westward transit flights as well as local flights out of Hong Kong. Conversely, the period March 18 through April 9 covers the local flights out of Yokota AB and the eastward transit flights back to the United States.

3.1 Flow Patterns

Before examining backward trajectories to determine the origins and paths taken by parcels sampled by the TRACE-P aircraft, it is informative to consider large scale flow patterns over the Northern Hemispheric Pacific Basin. The mean sea level pressure field during the first half of TRACE-P (Figure 1a) shows a well developed Siberian anticyclone (central pressure ~1032 hPa) near 50^{o}N, 90^{o}E as well as an intense Aleutian cyclone (central pressure ~990 hPa) near 55^{o}N, 170^{o}W. The subtropical anticyclone between California and Hawaii (~ 35^{o}N, 140^{o}W) has a central pressure of ~ 1026 hPa and covers a smaller area than the previously mentioned systems. Pressure patterns during the second half of TRACE-P (Figure 1b) are considerably different than earlier. The Siberian anticyclone now is ~ 10 hPa weaker and more diffuse. The Aleutian cyclone also is considerably weaker (~ 20 hPa greater pressure), and it has split into two centers. One is located over extreme northern Japan, while the second is near the Gulf of Alaska. The oceanic subtropical anticyclone is becoming more widespread although its central pressure has changed little.

Several studies have indicated that middle latitude cyclones forming or intensifying near eastern Asia are a major transport mechanism of Asian pollutants (e.g., *Jaffe et al*. [1999], *Kaneyasu et al*. [2000]). Thus, it is important to note that the Aleutian cyclone in Figure 1 a,b is not a single event, but instead represents the composite of numerous individual middle latitude transient cyclones that propagate through the region.

We examined daily sea level pressure charts during TRACE-P to identify the individual cyclones in the area. All cyclones having a central pressure less than 1016 hPa at some time during their lives were tracked. Ten cyclones met this criterion during the first half of TRACE-P (Figure 2a). Some of the cyclones begin over eastern Asia; others begin over the coastal region; and two develop over the western Pacific. The oceanic cyclones generally represent secondary developments associated with earlier "parent" storms. The ten cyclones follow a coherent path across the North Pacific Ocean, consistent with the well defined pressure gradient in Figure 1a. Their average lifetime (with a central pressure < 1016 hPa) is 5.2 days, and their average central pressure during this period is 988 hPa. The cyclones generally reach maximum intensity as they approach the Aleutian Islands (Figure 1a). Figure 3 contains satellite imagery for four TRACE-P flights during the first half of the period. Although the flight tracks that are superimposed are considerably south of the major cyclone centers seen in Figure 2, the flights do intercept the elongated cloud bands associated with the southern portions of cold fronts that extend southward from the cyclones.

More cyclones occur during the second half of TRACE-P (Figure 2b) than during the first half (12 vs.10 cyclones). However, these twelve storms have a considerably higher mean central pressure (996 vs. 988 hPa) and shorter lifetime (4.1 days vs. 5.2 days) than seen earlier. The storm tracks also are much less coherent than during the first half of the mission, as reflected in the weaker mean pressure gradients in Figure 1b. Some of the cyclones follow relatively short paths near Japan before decaying, while others have longer paths that extend nearly to Alaska. Many TRACE-P flights during this period are out of Yokota AB, Japan, and these higher latitude flights generally travel closer to the cyclone centers than did flights out of Hong Kong. Satellite imagery for selected

TRACE-P flights near wave cyclones are shown in Figure 4. It is clear that middle latitude cyclones greatly influence flow patterns during TRACE-P. Papers that examine details of chemical transport by cyclones during TRACE-P include *Avery et al*. [this issue], *Hannan et al*. [this issue], and *Miyazaki et al*. [this issue]. *Chen et al*. [1991, 1992] presented a climatology of cyclones that form near eastern Asia, while *Whittaker and Horn* [1984] considered cyclogenesis over the entire Northern Hemisphere.

Streamlines representing the time-averaged large-scale flow during the two halves of TRACE-P were obtained by averaging winds on the individual days. At the surface during the first half of the period (Figure 5g), when many TRACE-P flights are out of Hong Kong, there is persistent offshore flow north of ~35^{o}N. South of this region, however, the flow is more parallel to the coastline, with some onshore flow over Southeast Asia. There is strong cyclonic circulation associated with the Aleutian cyclone and strong anticyclonic flow around the subtropical high. Northeasterly trade winds dominate the tropical latitudes. Thus, there is considerable low level flow into the Southern Hemisphere. The Intertropical Convergence Zone (ITCZ) is not well defined over most of the tropical Pacific. However, as will be seen later, the northeasterly trades do contain bands of speed convergence which produce precipitation. The South Pacific Convergence Zone (SPCZ) stretches southeastward from Indonesia into the southcentral Pacific Basin.

During the second half of the TRACE-P period (Figure 5h), the streamline pattern generally appears less defined than before. There is more diffuse anticyclonic flow around the subtropical high, and less organized mid-Pacific middle latitude flow. The mean offshore flow from Asia also is less pronounced. These differences are due to the weakening of the Siberian anticyclone and the various middle latitude cyclones that form and remain in the area (Figure 2b). Nonetheless, strong offshore flow is observed on some individual flight days (not shown).

The time averaged flow patterns at 700 hPa (Figure 5 e,f, ~10,000 ft) and 500 hPa (Figure 5 c,d, ~18,000 ft) also show the changes that occur between the two halves of the TRACE-P period. Westerly flow dominates most of the midlatitude North Pacific Basin. Thus, there is widespread offshore flow from most of Asia and Southeast Asia. A subtropical anticyclone near 20^{o}N, 150^{o}E is evident at each pressure level during both halves of the mission. Pronounced anticyclonic circulation develops at 700 hPa near 25^{o}N, 150^{o}W during the second half of the mission. The changes in cyclonic flow associated with the splitting of the Aleutian low (Figure 1) (due to the differing storm tracks in Figure 2) also are seen at these middle tropospheric levels.

Since streamline patterns at 300 hPa (~30,000 ft) generally are similar to those at 500 hPa (Figure 5 c,d), they are not shown here. However, it is informative to examine time averaged wind speeds (isotachs) at 300 hPa (Figure 5 a,b) to determine the location and intensity of the jet stream. The Japan jet stretches west to east across the Pacific, extending back to Africa on the west to the coast of Canada on the east. This easterly flowing jet exhibits peak mean speeds of ~65 m s^{-1} at 300 hPa near Japan during the first half of the period. Mean speeds decrease rapidly south of the jet core, such that speeds at Hong Kong (22^{o}N, 114^{o}E), the base for most flights during this phase of TRACE-P, are only ~30 m s^{-1}. The jet exhibits only minor day-to-day variations in location and strength during this period. The strength of the jet is typical of the season. Cross sectional analyses (shown later) indicate that strongest winds actually occur at 200 hPa (~39,000 ft); however, the TRACE-P aircraft seldom reached this high altitude. Although the axis of the jet stream changes little as spring arrives (Figure 5 d), greatest mean speeds do weaken considerably, to only ~50 m s^{-1}. Finally, one should note the subtropical branch of the jet stream that appears as an elongation of the 20 m s^{-1} isotach near 10°N, 150°W. This southern branch of the jet stream is much weaker than the Japan jet, undergoing little change during the two halves of the mission.

3.2 Precipitation and Lightning

Precipitation is an important factor in atmospheric chemistry. For example, scavenging of soluble species by precipitation can deplete their concentrations (e.g., *Cohan et al*. [1999], *O'Sullivan et al.* [1999]). Furthermore, precipitation is due to rising motion that can transport species to higher altitudes. Precipitation in the middle latitudes often is due to well developed low pressure centers and their associated frontal systems (e.g., those in Figure 2). However, in the tropics, heavy rain can be associated with relatively subtle areas of low level convergence (tropical cyclones are the exception).

Lightning generally is confined to deep convective clouds that contain strong updrafts and have ice in their upper reaches. Thus, clouds producing lightning are expected to be important mechanisms by which surface-based chemical species are rapidly transported to higher altitudes where they can be quickly carried horizontally to distant locations by the relatively strong upper tropospheric winds. Furthermore, lightning is a source of nitrogen oxides in the atmosphere [e.g., *Ehhalt et al*., 1992; *Lawrence et al*., 1994].

Plate 1 shows the distribution of satellite-derived precipitation rates during TRACE-P. Patterns of satellite-detected lightning are shown in Plate 2. Widespread precipitation blankets middle latitude portions of the North Pacific Basin during both halves of TRACE-P (Plate 1), and some lightning is detected (Plate 2). This precipitation is associated with the middle latitude cyclones that traverse the region (Figure 2). The precipitation pattern is more coherent during the first half of the mission, consistent with the better defined storm tracks during that period (Figure 2). There also is more lightning over the western Pacific between 30°-35°N during the first half of the mission. During the second half, precipitation and lightning are enhanced west of Hawaii, centered near 20°N, 180°E.

Although precipitation over Asia is less widespread than over the Pacific (Plates 1 and 2), there are pockets of enhanced precipitation over northern and central Asia, especially during the second half of the mission. Areas of abundant lightning are located over India and Southeast Asia, again mostly during the second half. Farther removed from the flight area, a large area of precipitation and lightning is centered near Indonesia near the junction of the monsoon trough and the SPCZ. This area decreases during the second half. The ITCZ has a double structure, producing a band of precipitation (but relatively little lightning) on each side of the equator, especially prominent during the second half of the mission. This double structure is common during spring [*Hu et al.,* 2001; *Waliser and Gautier*, 1993; *Fuelberg et al*., 2001]. The trajectories described in the next section indicate that numerous TRACE-P flights intercepted air from the various areas of precipitation and lightning described above.

Patterns of mean outgoing long wave radiation (OLR, Figure 6) are consistent with the precipitation fields. Areas of relatively small OLR correspond to tall, cold cloud tops that correspond to precipitation regions. Conversely, areas of enhanced OLR represent either generally clear areas or regions with shallow, less widespread cloudiness.

3.3 Trajectory Analyses

Backward trajectories document the histories of air parcels sampled by the aircraft during TRACE-P. As described in Section 2, we calculated 5-day backward trajectories for locations along the DC-8 and P-3B flight tracks. Each flight and its associated trajectories were placed into one of three groups—transit flights to and from Asia, flights out of Hong Kong, and flights out of Yokota, Japan. Within each geographic category, trajectories along the various flight legs were grouped according to aircraft altitude (i.e., lower troposphere (below 850 hPa, below ~5,000 ft), middle troposphere (550 to 450 hPa, between ~16,000 and 21,000 ft), and upper troposphere/lower stratosphere (above 300 hPa, above ~30,000 ft). Plate 3 contains trajectories for the DC-8's transit flights between Asia and California. The color code indicates trajectory altitudes during the 5-day computational periods, while red circles show locations of the trajectory arrivals along the flight tracks, and red X's show locations 5 days earlier. The plotted trajectories within each altitude category generally arrive along the flight tracks at 10 min. intervals of flight time, corresponding to a separation of 90 km at a nominal aircraft ground speed of 150 m s^{-1} (~ 300 kt). Since flight tracks of the P-3B aircraft generally covered similar areas as the DC-8, its backward trajectories are similar to those of Plate 3 and are not shown here to conserve space.

Most air sampled along lower tropospheric portions of transit flights north of 30^{o}N or west of 140^{o}E (Plate 3c) passes over Japan and/or parts of Asia and then descends while approaching the aircraft. Conversely, air sampled in transit flight segments near 20^{o}N and east of 140^{o}E arrives from the east, reflecting the trade wind flow regime. However, going farther back in time, some air had traveled in the middle latitudes and then curved southward and descended around the eastern edge of the subtropical anticyclone off the

California coast before reaching the trade wind regime. *Martin et al.* [2002] described similar broadly circular paths during PEM Tropics-B. They found that upper tropospheric emissions from Asia required 2-3 weeks to travel east, then south, and finally west to reach the coast of New Guinea in the lower troposphere.

There were many middle tropospheric flight segments along the transit flights, and parcels sampled at those altitudes travel over a variety of locations (Plate 3b). Most parcels originate west of their sampling locations due to the prevailing westerly winds (Figure 5). Although many remain over the Pacific Ocean during the entire 5-day period, a smaller number pass over southern India or Southeast Asia, with some nearly reaching the equator. These are regions of abundant convection and lightning (Plate 2). Some higher altitude parcels (e.g., those colored red) extend back to northern Africa.

The trajectories of air sampled in the upper troposphere/lower stratosphere of the transit flights (Plate 3a) travel the farthest during the 5-day period due to the relatively strong upper level westerly winds. Some parcels follow an almost west to east path, extending back to northern Africa before the end of the 5-day period. Some may have previously passed over North America, and may be circumnavigating the Earth. A second group of trajectories originates near or even south of the equator and follows a clockwise path before joining the main west to east track. Some remain over water the entire period, while others pass over Southeast Asia or India. These trajectories tend to represent the southern portions of the transit flights. Their paths are due to the semi-permanent anticyclone located east of the Philippines in the middle and upper troposphere (Figure 5). Relatively few trajectories pass over central or northern Asia.

Air parcels sampled during flights out of Hong Kong generally have different origins and paths from those sampled during the transit flights. In the lower troposphere (Plate

4c), there are two main trajectory groupings. One group stays over water during the entire period, with most remaining near the surface (the black and purple colors). These trajectories represent tropical air in advance of the frequent cold fronts that traveled southeastward from Asia before becoming stationary near Hong Kong. A second group of trajectories originates over central Asia 5-days earlier, and then travels southeastward, slowly descending into the lower troposphere. These parcels represent post cold frontal air exiting the continent. The trailing segments of decaying fronts south of Hong Kong and Japan are a complex region where previously continental air is blended with more maritime tropical air. For example, *Hannan et al*. [this issue] describe cases in which the previously outflowing continental air stagnates in the subtropics but later comprises the warm conveyor belt of a subsequent eastward advancing wave cyclone.

Air sampled in the middle troposphere during the Hong Kong flights (Plate 4b) exhibits two major origins. Some trajectories remain over the Pacific, following tightly curved clockwise paths around the anticyclone near the Philippines (Figure 5). These trajectories originate in the deep tropics, possibly even the Southern Hemisphere if the calculation period were extended beyond 5 days. Parcels encountered by the aircraft along more northerly portions of the flights originate over Africa and travel almost due east toward the aircraft. These more northerly flight segments occur in regions of westerly flow (Figure 5). Air encountered in the upper tropospheric legs of the Hong Kong-based flights exhibits these same two major paths (Plate 4a). As noted previously, equatorial Africa and Southeast Asia are regions of abundant precipitation and lightning (Plates 1 and 2). The deep tropical or equatorial origins of some parcels again is noteworthy.

Backward trajectories for flights out of Yokota AB, Japan (Plate 5) reflect its more northerly location and the transition from winter to springtime flow patterns described earlier. In the lower troposphere (Plate 5c), the aircraft frequently sampled descending post-frontal continental air associated with the Siberian anticyclone. Some paths were over highly industrialized regions of Japan and China (e.g., Shenyang, Lanzhou, Chongqing, and Guangzhou [*Newell and Evans*, 2000]). Only the southern most portions of a few flights sampled pre-frontal air having a tropical origin. Thus, these encounters were less common than observed out of Hong Kong (Plate 4c). Most parcels sampled in the middle and upper troposphere (Plates 5 b and a) originate from the west, traveling in the middle latitude band of prevailing westerlies, including the strong Japan jet described earlier (Figure 5). One should note that few trajectories pass over central and northern Europe, and only a relatively small number passes over southern Europe and the Mediterranean Sea during the 5-day period. Instead, most trajectories travel farther south. The more northerly paths seem rather unlikely if the computational period were extended beyond five days. This suggests that relatively fresh European air was sampled infrequently during TRACE-P.

4. Representativeness of the TRACE-P Period

To interpret the significance of the transport processes and chemical evolution observed during TRACE-P, it is important to determine whether the wind and precipitation patterns represent a typical February through early April period as defined by climatological averages. The El Nino/Southern Oscillation (ENSO) phenomenon is a major factor leading to interannual climate variability. Survey descriptions of ENSO are provided by *Philander and Rasmusson* [1985], *Philander* [1990], and *Trenberth* [1997].

The phase of ENSO during TRACE-P was assessed using the Multivariate ENSO Index (MEI) which employs six observed variables over the tropical Pacific (sea-level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface air temperature, and total cloud fraction [*Wolter and Timlin* 1993, 1998; and the CDC web site (http:// www.cdc.noaa.gov/~kew/MEI/]. The index has been calculated for twelve overlapping bi-monthly periods (December-January, January-February, …, November-December), beginning with year 1950 (52 complete years). The CDC web site ranks these values, with the value 1 denoting the strongest La Nina case for that bi-monthly period, and the value 52 denoting the strongest El Nino case. Using terciles to group the MEI results, ranks 1-17 denote weak to strong La Nina periods, 18-35 represent near normal conditions, and 36-52 denote weak to strong El Nino periods.

An extended period of cold phase (La Nina) conditions began in mid 1998 (not shown) and persisted through mid 2001 [*Waple et al*., 2002]. There was considerable variability in La Nina’s strength during this three year period. Table 1 presents MEI rankings for several recent GTE missions. The PEM Tropics-B Experiment during Spring 1999 was conducted during a strong La Nina event (MEI rankings of 11). Specific MEI values during TRACE-P (Table 1) are 17 and 23. Thus, TRACE-P began during La Nina conditions, but ended in the neutral category. Conditions became more strongly neutral later in 2001—after TRACE-P had ended. *Waple et al*. [2002] note that strongest cold phase conditions during the three year La Nina event occurred during each Northern Hemispheric winter, followed by weakening during each spring season. These MEI-based determinations of ENSO phase generally agree with those based on sea surface temperature alone (e.g., the Japan Meteorological Agency (JMA) Index (not shown)).

To examine the representativeness of the TRACE-P period in greater detail, we calculated vector departures between mean winds during the 2001 mission period and those from long term climatology (1979-1995). That is, the climatology was subtracted from the TRACE-P mean, with the resulting difference fields expressed as streamlines. The two halves of the TRACE-P period again are examined separately since conditions in the middle latitudes change rapidly during the transition from winter to spring, and since flight tracks during the two halves are quite different (Hong Kong vs. Yokota AB). When examining the wind anomaly streamlines in Figure 7, it is useful to compare them with the actual TRACE-P flow patterns described earlier (Figure 5).

Streamlines of the surface wind anomaly do not exhibit well defined large-scale patterns over the Asian coast during either half of TRACE-P (Figure 7 g,h). And, magnitudes of the surface wind speed anomaly (not shown) are less than 2 m s^{-1} over most of the coastal area during both halves. Thus, low level transport from Asia during TRACE-P appears to be near normal. Farther east, the anticyclonic anomaly near 50^{o}N, 170^{o}W during the first half of the mission indicates that the subtropical high pressure region (Figure 5) is stronger than climatology. The intensification and northward displacement of this anticyclonic anomaly during the second half of the period correspond to the weakening of the Aleutian cyclone near Alaska and the change in the Pacific storm track seen in Figure 2. Finally, the tropical easterly trade winds are stronger than normal during the first half of TRACE-P, consistent with the enhanced Walker Circulation that occurs during La Nina events [*Philander*, 1990; *Waple et al*., 2002]. Conversely, the trade wind anomaly is poorly defined during the second half of the period, reflecting the spring warming of the eastern Pacific and weakening of La Nina conditions

Streamlines of vector wind departures at 300 hPa (Figure 7 c,d) are consistent with the transition from cold phase to neutral conditions that occurs during TRACE-P. *Arkin* [1982] found an anomalous couplet of cyclonic circulation centers in the upper troposphere during periods of relatively cold SSTs. His anomalous circulation centers straddled the equator (i.e., centers north and south of the equator). Those features were observed clearly during the strongly cold phase PEM Tropics-B period (Figure 4 of *Fuelberg et al*. [2001]). However, the TRACE-P anomalies are not as well defined due to the weaker La Nina event, and the anomalies change considerably during the second half of the period as the ENSO shifts to neutral (Figure 7 c,d). *Waple et al.* [2002] observed upper level westerly wind anomalies over the central and eastern tropical Pacific during early 2001 that are consistent with La Nina periods, and those are evident to some extent in Figure 7. The anomalies at 700 hPa (Figure 7 e,f) generally are similar to those at 300 hPa.

Patterns of OLR during TRACE-P depart considerably from climatology in the tropical latitudes, consistent with the La Nina conditions (Figure 7 a,b). There is a negative anomaly of ~30 W m^{-2} over portions of Southeast Asia and Indonesia. Conversely, a positive anomaly of approximately the same magnitude is located near the tropical portion of the Date Line. This dipole pattern indicates that tropical convection, with its relatively cold cloud tops, is displaced to the west of its usual position, reflecting a La Nina related enhancement of the monsoon [*Waple et al*., 2002]. These precipitation shifts are associated with enhanced ascending motion over the western Pacific and Indonesia (not shown) and anomalous subsidence over the central Pacific. These shifts in precipitation, OLR, and vertical motion reflect an enhanced east-west Walker circulation over the Pacific Basin and a suppressed north-south Hadley circulation over the central Pacific that is characteristic of La Nina events [*Waple et al*., 2002].

In summary, objective measures (e.g., the MEI) indicate weak La Nina conditions during the first half of TRACE-P, followed by a shift to near neutral conditions during the second half. Flow and precipitation anomalies generally are consistent with this transition.

5. Comparisons Between TRACE-P and PEM West-B

The second phase of NASA's Pacific Exploratory Mission-West (PEM W-B) experiment was conducted off the east coast of Asia between February 7 and March 15, 1994 [*Hoell et al*., 1997]. PEM W-B covered the same geographic area as TRACE-P, but during a somewhat earlier and briefer time period (February 23 – April 9, 2001) such that TRACE-P includes a greater sampling of spring time conditions. Since chemical data from the two missions likely will be compared, it is appropriate to compare their flow patterns. *Merrill et al*. [1997] give a complete meteorological overview of PEM W-B.

Table 1 indicates that PEM W-B occurred during a neutral phase of ENSO (MEI ranking of 31), while TRACE-P occurred during a neutral to slightly cold phase (average MEI ranking of 20). Thus, the MEI rankings are on opposite ends of the neutral tercile. However, unlike TRACE-P, the MEI ranks during PEM W-B show little variation during the six month period centered on the mission.

Streamlines derived from the mission-averaged winds illustrate flow patterns during the two periods (Figure 8). Although the two missions do not occur on the same days or last for the same length of time, these streamlines do describe the periods during which the chemical data were collected. Streamlines throughout the troposphere (surface, 700 hPa, and 300 hPa) indicate that basic flow patterns during PEM W-B and TRACE-P generally are similar (Figure 8 c-h). However, at the surface, the Aleutian low is positioned somewhat differently during the two missions. And, an important difference at 300 hPa is that the Japan jet is ~10 m s^{-1} stronger during PEM W-B than during TRACE-P, and the jet axis is more zonal during PEM W-B. Thus, stronger upper level eastward transport from southern Asia occurs during PEM W-B. Latitude-height cross sections of the mission averaged zonal wind along 140^{o}E (Figure 8 a,b) illustrate transport from Asia. The two cross sections exhibit strong similarities. Specifically, westerlies dominate the middle latitudes, with the jet stream centered near 200 hPa. Conversely, easterlies (negative values) extend throughout much of the column in both the tropics and high latitudes of both missions. However, as noted above, cross sections through different longitudes would indicate greater differences (e.g., the contrasting jet axes).

Streamlines of the vector wind difference between the two periods (i.e., TRACE-P minus PEM W-B) were calculated (Figure 9 b-d) to isolate any differences in flow that might not be apparent in the basic streamlines of Figure 8. One prominent difference is the enhanced middle latitude anticyclonic flow during TRACE-P that occurs throughout the troposphere. Conversely, there is enhanced cyclonic flow during TRACE-P near the Aleutian Islands.

Merrill et al. [1997] show single trajectories for six locations during PEM W-B. Those trajectories agree closely with trajectories at similar locations during TRACE-P (Plates 3-5). This is expected since flow patterns of the two missions are quite similar.

Middle latitude cyclones are ~20% more frequent during TRACE-P than PEM W-B. Specifically, the five week PEM W-B period contains fifteen middle latitude cyclones with central pressures less that 1016 hPa, yielding an average frequency of 3 cyclones per week, compared to 3.3 cyclones per week during the first half of TRACE-P and 4 cyclones per week during the second half of TRACE-P. The PEM W-B cyclones exhibit an average pressure of 991 hPa which is between values during the two halves of TRACE-P (988 hPa and 996 hPa). The average lifetime of 4.2 days is similar to that observed during TRACE-P.

Anomalies of OLR for TRACE-P (Figure 7) are very similar to those of PEM W-B (not shown). Both exhibit negative anomalies (~25 W m^{-2}) over Indonesia due to enhanced convection, and positive anomalies over the central tropical Pacific due to suppressed convection. Thus, the TRACE-P minus PEM W-B OLR pattern (Figure 9a) mostly contains differences < 20 W m^{-2} over the Pacific Basin. The greater OLR values over southcentral Asia during TRACE-P are due to the warmer temperatures occurring during that later occurring mission.

To summarize, flow patterns and precipitation during TRACE-P generally are similar to those during PEM W-B.

6. Conclusions

The TRAnsport and Chemical Evolution over the Pacific (TRACE-P) Experiment was conducted over the Pacific Basin between February and April 2001 to investigate chemical outflow from Asia and its evolution during eastward transport across the Pacific. Meteorological conditions play a critical role in the distribution and transport of chemical species, and this paper has described atmospheric transport and precipitation patterns over the TRACE-P domain. TRACE-P occurred during the transition from winter to spring, and during a rapid transition from a weakly cold to near neutral phase of the ENSO cycle. Therefore, atmospheric flow patterns exhibited considerable change during the seven week period. Transport off the Asian continent was frequent and widespread. This was attributable to the Siberian anticyclone and to frequent middle latitude cyclones that formed near the east coast of Asia and then propagated eastward across the North Pacific. Wide swaths of clouds and precipitation accompanied these cyclones. Abundant precipitation and lightning (indicating deep convection) occurred over Southeast Asia and Indonesia.

Five-day backward trajectories revealed that the TRACE-P aircraft had sampled air from wide variety of sources. Some of the sampled parcels had remained over the Pacific during the entire 5-day period. Others originated over Southeast Asia, Africa, and central Asia. Relatively few trajectories passed over central and northern Europe. Some trajectories originated in the deep tropics. Lower tropospheric flight segments out of Hong Kong sampled both pre-frontal maritime air as well as post-frontal air from the Asian continent. Conversely, low-level flight segments out of Yokota, Japan mostly sampled post-frontal Asian air. Southern portions of middle and upper tropospheric flight segments from Hong Kong sampled air previously in the deep tropics, while the more northerly flight segments sampled air that originated from the west (e.g., passing over central Africa and India). Upper level segments from Yokota mostly sampled air with a westward history.

TRACE-P began during a slightly cold phase of the ENSO cycle, but the cycle rapidly changed to near neutral conditions by the end of the mission. Precipitation in the deep tropics was displaced west of its climatological position—consistent with La Nina events. Tropospheric flow patterns generally agreed with those observed during previous La Nina events. However, the La Nina influence was much less pronounced than observed during the strongly cold phase PEM Tropics B mission. Major flow patterns during TRACE-P generally were similar to those occurring during the PEM West-B mission that was conducted off the coast of Asia during early 1994.

Acknowledgments. This research was sponsored by the NASA Tropospheric Chemistry Program. The TRACE-P meteorological team expresses its sincere appreciation to the meteorological staffs at Hong Kong Observatory and the U.S. Air Force at Andersen AB (Guam), Yokota AB (Japan), and Kadena AB (Okinawa). These individuals provided valuable insight into local weather conditions. We appreciate the support of Vickie Connors, Jim Raper, and Richard Bendura in helping with the many scientific, logistical, and managerial matters. The crews and support staff of the DC-8 and P3-B aircraft always were most helpful during the preparations and deployments of TRACE-P. We thank Mike Cadena, Erika Harper, and Roy Chesson of the SAIC - GTE Project Office for their assistance during all phases of the project. Dennis Buechler at NASA Marshall Space Flight Center provided the LIS lightning images, and Dr. Yuanlong Hu (MIT) assisted with editing the manuscript.

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Table 1. Rankings of the Multivariate ENSO Index (MEI) during recent GTE missions. Rankings 1-17 denote weak to strong La Nina periods, 18-35 represent near normal conditions, and 36-52 denote weak to strong El Nino periods [*Wolter and Timlin* 1993, 1998; and the CDC web site (http:// www.cdc.noaa.gov/~kew/MEI/].

GTE Mission	Period	MEI Rankings
PEM West-A	Sept-Oct 1991	43
PEM West-B	Feb-Mar 1994	31
PEM Tropics-A	Aug-Sept, Sept-Oct 1996	21, 19
PEM Tropics-B	Feb-Mar, Mar-Apr 1999	11, 11
TRACE-P	Feb-Mar, Mar-Apr 2001	17, 23

Figure Captions

Figure 1. Mean sea level pressure (hPa) for the two halves of the TRACE-P period, a) 23 February – 17 March 2001 and b) 18 March – 9 April 2001.

Figure 2. Tracks of cyclones affecting TRACE-P. Solid circles denote locations where the mean sea level pressure of a cyclone first became less than 1016 hPa, while stars denote the last location of this pressure. Results for the two halves of TRACE-P are shown.

Figure 3. Visible imagery from the GMS satellite on selected days when TRACE-P flights intersected frontal cloud bands during the first half of the period. Flight tracks are indicated on the images.

Figure 4. Visible imagery from the GMS satellite on selected days when TRACE-P flights intersected frontal cloud bands during the second half of the period. Flight tracks are indicated on the images.

Figure 5. (a-b) Mean isotachs at 300 hPa during the two halves of TRACE-P. (c-h) Mean streamlines at the surface, 700 hPa, and 500 hPa during the two halves of TRACE-P. Major cyclonic and anticyclonic circulation centers are labeled “L” and “H”, respectively.

Figure 6. Mean outgoing longwave radiation (W m^{-2}) during the two halves of TRACE-P.

Figure 7. (a-b) Departure of outgoing longwave radiation (W m^{-2}) during the two halves of TRACE-P from their respective long term climatological means. (c-h) Streamlines of the vector departure of winds during the two halves of TRACE-P from their respective long term climatological means. Cyclonic and anticyclonic anomalies are indicated by "L" and "H", respectively.

Figure 8. (a-b) Latitude-height cross section of the zonal wind (m s^{-1}) along 140^{o}E longitude during the TRACE-P and PEM WEST-B missions. (c-d) Mean isotachs at 300 hPa during the TRACE-P and PEM WEST-B missions. (e-h) Mean streamlines at the surface and 700 hPa during the TRACE-P and PEM WEST-B missions. Major cyclonic and anticyclonic circulation centers are labeled "L" and "H", respectively.

Figure 9. (a) Difference in outgoing long wave radiation (W m^{-2}) between the TRACE-P and PEM WEST-B missions. (b-d) Streamlines of the vector wind difference between the TRACE-P and PEM WEST-B missions at the surface, 700 hPa and 300 hPa.

Plate Captions

Plate 1. (a-b) Satellite-derived rainfall for the first and second halves of TRACE-P derived from the SSM/I instrument. Data provided by NOAA.

Plate 2. (a-b) Lightning data for the first and second halves of TRACE-P detected by the Lightning Imaging Sensor. Due to the nature of the satellite's orbit, the data are confined to ± 35^{o} latitude. Data provided by NASA Marshall Space Flight Center (http://thunder.msfc.nasa.gov/lis.html).

Plate 3. Five-day backward trajectories arriving at DC-8 aircraft locations along the eastbound and westbound transit flights of TRACE-P. (a) Trajectories arriving at aircraft pressure altitudes of 300 hPa or less, (b) Trajectories arriving at aircraft pressure altitudes between 550 and 450 hPa, and (c) Trajectories arriving at aircraft pressure altitudes of 850 hPa and greater. Trajectories within a given altitude category generally arrive at the aircraft tracks at intervals of 10 min. flight time. Trajectory altitudes are denoted by the color scale, while circles denote the aircraft arrival positions, and stars indicate locations five days earlier.

Plate 4. As in Plate 3, but for trajectories arriving at the DC-8 flights out of Hong Kong.

Plate 5. As in Plate 3, but for trajectories arriving at the DC-8 flights out of Yokota AB, Japan.